

Abundance Profiles in Low-mass Galaxies

Chip Kobulnicky

*UCSC/Lick Observatory
Santa Cruz, CA 95064*

Abstract. The nitrogen and oxygen abundances in the warm ionized gas of low-mass, metal-poor galaxies appear surprisingly homogeneous considering the prevalence of large HII regions, which contain hundreds of massive stars. Of the six galaxies with extensive optical spectroscopy, only the largest and most metal-rich, the LMC, shows evidence for a chemical gradient akin to those commonly seen in spirals. Furthermore, no significant localized chemical fluctuations are found in the vicinity of young star clusters, despite large expected chemical yields of massive stars. An ad-hoc fine-tuning of the release, dispersal and mixing rates could give rise to the observed homogeneity, but a more probable explanation is that fresh ejecta reside in a hard-to-observe hot or cold phase. In any case, the observations indicate that heavy elements which have already *mixed* with the warm interstellar medium are homogeneously *dispersed*. Mixing of fresh ejecta with the surrounding warm ISM apparently requires longer than the lifetimes of typical HII regions ($>10^7$ yrs). The lack of observed localized chemical enrichments is consistent with a scenario whereby freshly-synthesized metals are expelled into the halos of galaxies in a hot, 10^6 K phase by supernova-driven winds before they cool and “rain” back down upon the galaxy, creating gradual enrichments on spatial scales >1 kpc.

1. Introduction

Defining a sample of “low-mass” galaxies is immediately problematic because very few systems, especially those of low mass, have well-determined dynamical masses. Fortunately, optical luminosity correlates well with the dynamical mass inferred from galactic rotation curves (e.g., Tully & Fisher 1977), and it is a reasonable substitute parameter. For purposes of this review, I have taken “low-mass” to mean systems with M_B fainter than -18 . The luminosity criterion for a “dwarf” galaxy is variously taken to be $M_B > -18$ (Thuan 1983) or $M_B > -16$ (Tammann 1980; Hodge 1971).

Low-mass galaxies encompass a wide variety of nomenclature, including blue compact dwarf galaxies (BCDG), HII galaxies, dwarf elliptical galaxies (dE), irregular, and low surface brightness (LSB) galaxies. The chemical composition of their stars and gas may be measured by optical spectroscopy of emission lines from prominent HII regions (for warm ionized gas), absorption lines in stellar atmospheres (for stars), or X-ray spectroscopy of emission lines from highly ionized

atomic species (for hot diffuse gas). Here I consider only abundance measurements in the warm photo-ionized gas in and around HII regions. Since oxygen is the most easily measured element in HII regions, the terms “abundance” or “metallicity” should be read as the “abundance of oxygen relative to hydrogen.” Reviews of the abundances of other elements in stars (usually Fe) or hot coronal gas may be found elsewhere in this volume.

The topic of abundance profiles entails two distinct issues. 1) Do low-mass galaxies show *global* radial abundance gradients as large spiral galaxies (Searle 1971; Zaritsky, Kennicutt & Huchra 1994) often do? 2) Are there *localized* chemical fluctuations on spatial scales comparable to individual giant HII regions that might be due to heavy elements recently synthesized and released by massive stars (e.g., “self-enrichment”—Kunth & Sargent 1986; “local contamination”—Pagel, Terlevich, & Melnick 1986). Since chemical abundances are like fossils that record the previous star formation activity, both types of elemental variations contain information about the star formation and gas dynamical history of the host galaxy.

2. Radial Abundance Gradients

2.1. Object Selection

Reliable measurement of a chemical spatial profile requires knowledge of the chemical abundances spanning a range of radial distances. To date, the literature contains only a handful of low-mass galaxies with optical spectroscopic abundance determinations at five or more distinct locations. The nine such galaxies are summarized in Table 1, along with basic physical parameters necessary to interpret their abundance profiles. Most objects are relatively nearby and have Magellanic spiral or irregular morphology.

2.2. Oxygen Abundance Profiles

Figure 1 shows the oxygen abundance as a function of radius for the objects in Table 1 using the published galactocentric¹ radial distance and O/H measurements computed in the original references. The three LSB galaxies could not be shown because neither linear nor angular radial distances are given in the original reference. A single error bar is plotted to provide an estimate of the typical 1σ uncertainty when O/H is computed empirically from [O II], [O III] and H β line ratios rather than from a direct determination of the electron temperature via the [O III] λ 4363 line. For objects such as NGC 6822 and NGC 1569 which have O/H measurements using both methods, results from the direct method are shown with large symbols and results from empirical methods are shown with smaller symbols of the same type. Note that there is typically a systematic offset of 0.1—0.2 dex between the two methods, underscoring the need for direct O abundance determinations.

In Figure 1 there is no significant correlation of radial distance with oxygen abundance except in the LMC where the gradient is -0.048 ± 0.019 dex/kpc. In

¹deprojected for inclination in all cases except NGC 1569

Table 1. Low-Mass Galaxies with Abundance Measurements

Name	Morph	Dist. (Mpc)	M_B	$12+\log^a$ (O/H)	h_0^b (kpc)
NGC 6822	IBm	0.47 ^c	-14.88 ^c	8.19 ^d	— ^e
NGC 2366	SBm	2.83 ^c	-15.79 ^c	7.92 ^f	2.1 ^g
NGC 1569	IBm	1.72 ^c	-16.34 ^c	8.19 ^h	0.3 ^g
SMC	Im	0.058 ^c	-16.35 ^c	8.03 ⁱ	0.8 ^j
F365-1	Sm/LSB	45 ^k	-17.3 ^k	8.0 ^k	4.3 ^k
UGC 5999	Im/LSB	45 ^k	-17.7 ^l	8.0 ^k	4.3 ^m
UGC 5005	Im/LSB	52 ^k	-17.9 ^l	8.0 ^k	4.4 ^m
LMC	SBm	0.047 ^c	-17.73 ^c	8.03 ⁱ	1.9 ^j
NGC 4214	SBm	4.03 ^c	-17.82 ^c	8.19 ⁿ	1.7 ^g

^aOxygen abundances, $12+\log(\text{O}/\text{H})$ are nominal mean values for general reference only, neglecting the possibility of internal variations.

^bScale lengths, h_0 , in kpc are derived using the angular scale length of the B-band photometry from the listed reference in conjunction with the assumed distance in column 3.

^cFrom the self-consistent distance and magnitude tabulation of Richer & McCall (1995). See refs. therein.

^dPagel, Edmunds, & Smith (1980).

^eNo reliable published value.

^fPeimbert, Pena, & Torres-Peimbert (1986); see also Roy et al. (1996)

^gde Vaucouleurs et al. (1991); The angular disk scale length, h_0 , is derived from half light radius, R_d , assuming an exponential disk so that $R_d=1.678h_0$.

^hKobulnicky & Skillman (1997).

ⁱPagel et al. (1978); for the LMC region N4A, the Pagel et al. value of $12+\log(\text{O}/\text{H})=8.44$ has been replaced with a more recent measurement by 8.18 by Russel & Dopita (1990).

^jBothun & Thompson (1988).

^kde Blok (1997); assumes $H_0=75$.

^lde Blok (1997); estimated from R magnitude assuming $M_B \approx M_R + 0.7$ as is typical of other LSB galaxies in the sample.

^mde Blok (1997); scale length given is that for R band instead of B band.

ⁿKobulnicky & Skillman (1996).

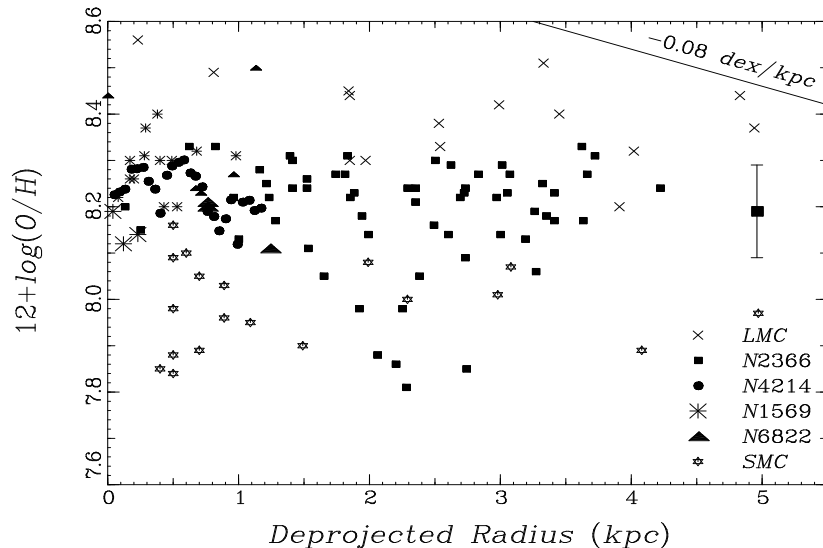


Figure 1. O/H versus deprojected radial distance in kpc for HII regions in low-mass galaxies. For all objects except the LMC, the slope of the O/H gradient is consistent with 0.00 ± 0.02 dex/kpc. However, more high quality spectra of HII regions at large radii are necessary to establish whether small gradients may exist.

all other cases the O/H gradient is less than 0.02 dex/kpc, formally consistent with zero. However, only the LMC, SMC, and NGC 2366 have abundance measurements over a large radial extent. High quality spectra of HII regions in the outer parts of other irregular galaxies will be necessary to detect small amplitude gradients, if they exist.

In large spiral galaxies there has been considerable discussion about which size parameter is the appropriate one to use in measuring radial profiles. Many authors have chosen the optical disk scale length, h_0 , (see discussions in Zaritsky, Kennicutt, & Huchra, 1994; Garnett et al. 1997) in lieu of a fixed linear size. The O/H ratio in low-mass galaxies as a function of optical scale length is shown in Figure 2. Only NGC 6822 is not plotted because it does not have a published value for h_0 . The interpretation is the same as Figure 1, in that the LMC is the only object with a significant abundance gradient, -0.097 ± 0.037 dex/ h_0 . A robust limit on the gradients in the other systems will require high-quality spectroscopy of HII regions beyond 2 optical scale lengths.

3. Localized Abundance Fluctuations

3.1. Do Chemical Fluctuations Exist?

Clusters of massive stars are capable of creating large localized chemical enrichments (Esteban & Peimbert 1995), yet in the vicinity of young starbursts in NGC 4214 (Kobulnicky & Skillman 1996) and NGC 1569 (Kobulnicky & Skillman 1997), no sizable O, N, or He anomalies are seen in the surrounding warm photoionized medium. NGC 5253 (Welch 1970; Walsh & Roy 1989; Kobul-

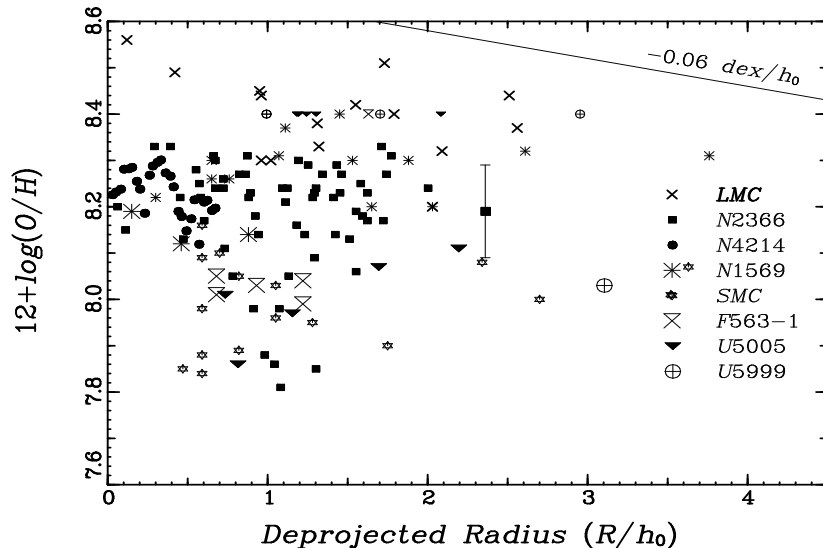


Figure 2. O/H versus deprojected radial distance in optical (B-band) scale lengths for HII regions in low-mass galaxies. The figure is qualitatively similar to Figure 1, with the addition of 3 LSB galaxies from de Blok (1997). Only the LMC shows a significant radial oxygen gradient.

nicky et al. 1997) remains the only well-established exception, containing central starburst region overabundant in nitrogen by a factor of 3 compared to the surrounding ISM. Further evidence for chemical homogeneity in the ISM around starbursts is provided by the two HII regions in the very metal-poor I Zw 18. Separated by ~ 50 pc, they show identical O and N abundances (Skillman & Kennicutt 1993; Martin 1996; Vilchez et al. 1997), even though the yield from a single massive star would be sufficient to measureably “pollute” either one.

A quantitative comparison of expected chemical pollution versus observed abundance fluctuations is shown in Figure 3 for the case of the super star cluster A in NGC 1569. The measured N/O ratio along a 45 arcsec strip adjoining the star cluster is plotted. The N/O ratio is a particularly robust measure of potential abundance fluctuations because it is relatively insensitive to errors in the adopted electron temperature. In Figure 3, no substantial variations beyond the measurement uncertainties are evident despite the sensitivity to the N or O yields of just a few massive stars. For example, the slightly-elevated N/O ratio seen at the position number 12 at the $35''$ mark could be caused by as few as two $40 M_{\odot}$ stars.

3.2. Is Dilution the Solution to Pollution?

Can the lack of observed enrichment be just due to rapid dispersal and dilution of the heavy elements? Not likely. Assuming an age of 10 Myr for cluster A, homogeneous dispersal within a sphere of a given radius, a filling factor for the ionized gas of 0.1, a gas density of 100 cm^{-3} , an IMF slope of -2.7 in the range $0.5\text{--}100 M_{\odot}$ (see Kobulnicky & Skillman 1997 for details), the expected N/O deviations for a variety of dispersal scales are shown with solid lines. Adopting any combination of inhomogeneous dispersal, higher cluster age, lower filling

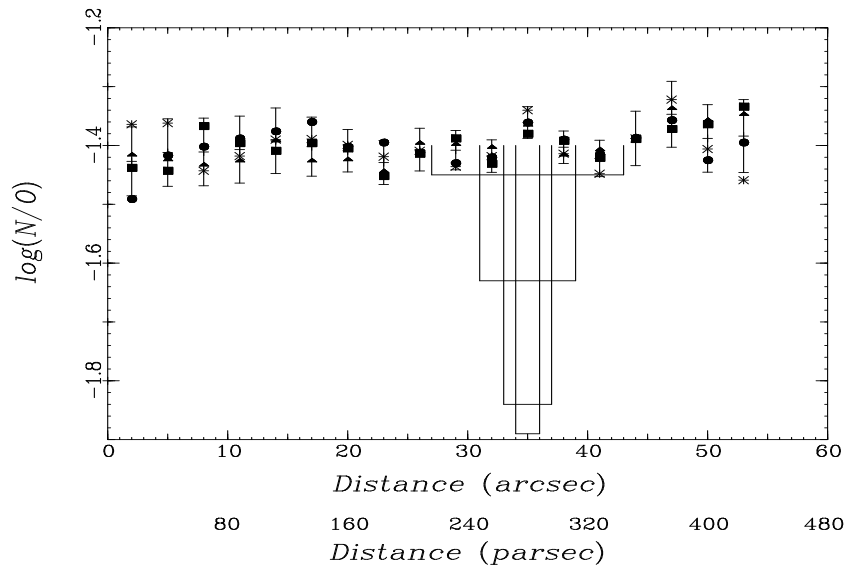


Figure 3. The N/O ratios along a $45''$ strip of the ISM adjoining cluster A in NGC 1569. The expected magnitude of chemical enrichment (predominantly O enrichment) is shown by solid lines for four different dispersal radii. The observed variations are small in comparison to predicted enrichments, suggesting some of the freshly-released elements are hidden in a hard-to-observe phase.

factor or lower average gas density will enhance the expected chemical variations. Given typical expansion speeds of supernova ejecta, the heavy elements *could* be dispersed through a larger region than the largest simulated volume, and thereby become undetectable. However, such an extreme rapid-dilution scenario requires a finely-tuned, ad hoc dispersal mechanism to maintain the appearance of homogeneity of scales of several hundred pc. It seems that the heavy elements produced by the massive stars (down to $20 M_{\odot}$) in cluster A are evidently not seen in the warm ionized medium.

Kunth & Sargent (1986) argued that objects more metal-poor than I Zw 18 should not be observed due to heavy element contamination from the current burst of star formation. In a small metal-poor galaxy like I Zw 18, a small number of O stars can produce significant chemical enrichment. Figure 4 sketches crudely the expected oxygen enhancement in a hypothetical primordial-abundance galaxy as a function of oxygen yield, gas mass/volume, and nff , the product of the volume-averaged gas density and filling factor. It helps illustrate that only a few solar masses of O are required to raise the oxygen abundance from primordial to that seen in I Zw 18 provided that only the inner few tens of pc are enriched. However, longslit spectroscopic surveys suggest that the O abundance is similar over several hundred pc, so perhaps several thousand O stars would be required to raise the abundance to the observed level.

3.3. Where Have all the Metals Gone?

Given the lack of visible chemical enrichment around major starbursts, several explanations could be considered. 1) *Perhaps the metals were never pro-*

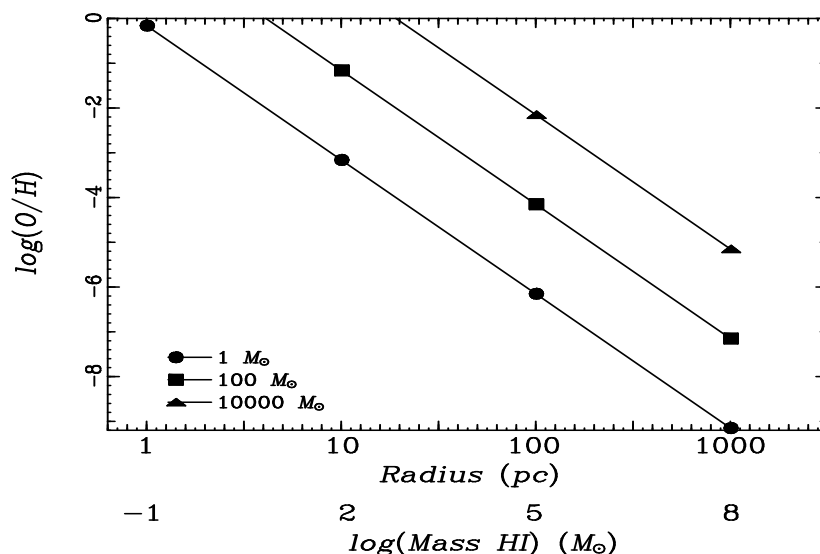


Figure 4. The resulting O/H ratio in a volume of gas initially of primordial composition assuming homogeneous dispersal of heavy elements throughout a sphere of a given radius. The lower x-axis labels show the approximate hydrogen gas mass enclosed in the given volume assuming nff , the product of mean gas density and filling factor is 1.0. The resulting O/H ratio is shown for yields of $1 M_{\odot}$, $100 M_{\odot}$, and $10,000 M_{\odot}$ of oxygen.

duced/released in the first place? If the number of massive stars originally present in the cluster has been overestimated based on the remaining stellar content, then the expected mass of heavy elements would be reduced. An abnormally low upper mass cutoff in the IMF, or an abnormally steep IMF could work to accomplish the observed effect. Yet, NGC 4214 and NGC 1569 do contain Wolf-Rayet stars, so clearly the most massive stars have been, and are still present in the bursts.

2) *An alternative suggestion requires that black holes left by supernovae from massive stars to engulf the metals produced by the progenitor (e.g., Maeder 1992).* This idea merits further theoretical investigation, but unless the lower mass limit for black hole formation, M_{BH} is considerably lower than $\sim 50 M_{\odot}$, then the reduction of chemical yields will be too minor to resolve this problem. See discussion elsewhere in this volume for current estimates of M_{BH} .

3) *The last, and most probable explanation for missing metals requires that the freshly-ejected metals reside in a hard-to-observe hot or cold phase (e.g., Tenorio-Tagle 1996).* Since supernovae and the superbubbles formed by concerted supernovae contain copious X-ray emitting material, hot gas is the preferred explanation. The Cas A supernova remnant, for example, contains between $4 M_{\odot}$ (Vink, Kaastra, & Bleeker 1996) and $15 M_{\odot}$ (Jansen, Smith, & Bleeker 1989) of X-ray emitting material, consistent with the amount of ejecta expected from the progenitor. The next generation of orbiting spacecraft should be able to measure the mass and metallicity of hot gas surrounding massive star

clusters and make a direct comparison to expectations based on starburst models.

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